

B_s Properties at the Tevatron

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Abstract. Recent results on B_s properties obtained by the CDF and DØ collaborations using the data samples collected at the Tevatron Collider in the period 2002 – 2006 were presented at the Hadron Collider Physics Symposium 2006 (Duke University, Durham). The measurements of B_s mass and width differences are discussed in details. Prospects on measurements of CP violation in B_s system are given.

Keywords: Bottom mesons, Mixing, Lifetime difference, CP violation

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INTRODUCTION

Run II at the Tevatron Collider started in 2001. The CDF and DØ experiments have successfully collected data since that time. Until February 2006 each experiment recorded data corresponding to an integrated luminosity of about 1.4 fb^{-1} . The analyses described in this paper are based on samples corresponding to luminosity from 0.18 to 1 fb^{-1} .

The CDF and DØ B physics programs benefit from production of all species of B hadrons at the Tevatron Collider. This leads to a possibility of systematic studies of such phenomena as B_s mixing, lifetime difference, rare decays and CP violation. Simultaneous measurements of relevant B_d quantities provide very good opportunities for cross-checks of the results by comparisons with B factories [1]. Though, there are more and more cases when the Tevatron B_d results have comparable or even better precision. The combined B_s and B_d results tighten the overconstraint of the CKM matrix elements. Any discovered inconsistency would indicate presence of the new physics outside of scope of the Standard Model (SM).

Table 1 lists the recent Tevatron B_s results. The results on B_s mixing, lifetime difference and CP violation will be discussed in details.

TABLE 1. Recent B_s results from Tevatron.

Quantity	CDF	$(\int \mathcal{L} dt, \text{fb}^{-1})$	DØ	$(\int \mathcal{L} dt, \text{fb}^{-1})$
$\Delta m_s, \text{ps}^{-1}$	$17.33^{+0.42}_{-0.21} \pm 0.07$	(1)	$17 - 21 @ 90\%$	(1)
$\Delta \Gamma_s, \text{ps}^{-1}$	$0.47^{+0.19}_{-0.24} \pm 0.01$	(0.260)	$0.15 \pm 0.10^{+0.03}_{-0.04}$	(0.800)
$\Delta \Gamma_{CP}/\Gamma_{CP}(B_s \rightarrow KK)$ [2]	$-0.08 \pm 0.23 \pm 0.03$	(0.360)	—	—
$c\tau_s, \text{ps}$	$1.381 \pm 0.055^{+0.052}_{-0.046}$	(0.360)	$1.398 \pm 0.044^{+0.028}_{-0.025}$	(0.400)
$Br(B_s \rightarrow \mu\mu) \times 10^7$ [3]	$< 1 @ 95\%$	(0.780)	$< 2.3 @ 95\% *$	(1)
$Br(B_s \rightarrow \mu\mu\phi)$ [3]	$< 6.7 \times 10^{-5} @ 95\%$	(Run I)	$< 4.1 \times 10^{-6} @ 95\%$	(0.450)
$Br(B_s \rightarrow D_s^{(*)+} D_s^{(*)-})$	—	—	$0.071 \pm 0.032^{+0.029}_{-0.025}$	(1)
$Br(B_s \rightarrow D_s^+ D_s^-)/Br(B_d \rightarrow D_s^+ D^-)$	$1.67 \pm 0.41 \pm 0.47$	(0.355)	—	—
$Br(B_s \rightarrow \phi\phi) \times 10^3$	$7.6 \pm 1.3 \pm 0.6$	(0.180)	—	—
$Br(B_s \rightarrow D_s^{*-} \mu^+ \nu X) \times 10^2$	—	—	$0.86 \pm 0.16 \pm 0.16$	(1)
$Br(B_s \rightarrow D_s 3\pi)/Br(B_d \rightarrow D^- 3\pi)$	$1.14 - 1.19$	(0.355)	—	—
$Br(B_s \rightarrow \psi(2S)\phi)/Br(B_s \rightarrow J/\psi\phi)$	$0.52 \pm 0.13 \pm 0.07$	(0.360)	$0.58 \pm 0.24 \pm 0.09$	(0.300)
Observation B_{s2}^{0*}	—	—	$135 \pm 31 \text{ ev.}$	(1)

* expected

B_s MIXING, LIFETIME DIFFERENCE AND CP VIOLATION

Time evolution of the neutral $B - \bar{B}$ systems, $B_d^0 - \bar{B}_d^0$ and $B_s^0 - \bar{B}_s^0$, is described by the Schrödinger equation:

$$i \frac{d}{dt} \begin{pmatrix} |B^0\rangle \\ |\bar{B}^0\rangle \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix} \begin{pmatrix} |B^0\rangle \\ |\bar{B}^0\rangle \end{pmatrix} \quad (1)$$

The mass eigenstates do not coincide with the corresponding flavor states (see e.g. [4]): $|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$, $|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$, where $|p|^2 + |q|^2 = 1$. Mass differences between the $B_{d(s)}$ mass eigenstates can be expressed through off-diagonal elements of the Hamiltonian from Eq. 1

$$\Delta m = M_H - M_L \approx 2|M_{12}|. \quad (2)$$

Corresponding lifetime differences are

$$\Delta\Gamma = \Gamma_L - \Gamma_H \approx \Delta m \Re(\Gamma_{12}/M_{12}) = 2|\Gamma_{12}|\cos\varphi, \text{ where } \varphi = \arg(-M_{12}/\Gamma_{12}). \quad (3)$$

The non-zero off-diagonal elements of the Hamiltonian lead to a property of B_d^0 and B_s^0 mesons to change flavor and transform into their antiparticles. This phenomenon is called oscillation or mixing. The oscillation frequency is proportional to the mass difference $\Delta m_{d(s)}$. The phase angle φ connects the quantities Δm and $\Delta\Gamma$ to the third measurable parameter $a_{fs} = \Im(\Gamma_{12}/M_{12}) = (\Delta\Gamma/\Delta m)\tan\varphi$, which determines CP violation in mixing. The value Δm_d is very well measured with the highest accuracy achieved at the BABAR and BELLE experiments [5]. The value $\Delta\Gamma_d$ is expected to be small due to double Cabbibo suppression ($\Delta\Gamma_d/\Gamma_d = (2.42 \pm 0.59) \times 10^{-3}$ [6] to be compared with the experimental result from BABAR and DELPHI: $\Delta\Gamma_d/\Gamma_d = (0.9 \pm 3.7) \times 10^{-2}$ [5]). The SM value $a_{fs}^d = -(5.0 \pm 1.1) \times 10^{-4}$ [7, 25] could be enhanced in presence of new physics up to 0.01 [4, 7] (updated calculations are in [26]). The Standard Model predictions for these parameters for B_s system are following: $\Delta m_s \sim 20 \text{ ps}^{-1}$ [8, 9], $\Delta\Gamma_s/\Gamma_s = (7.4 \pm 2.4) \times 10^{-2}$ [6] (more recent theoretical calculations are available in [27]) and $a_{fs}^s = (2.1 \pm 0.4) \times 10^{-5}$ [7, 25]. New phenomena could influence differently the B_d and B_s systems.

B_s⁰ – \bar{B}_s^0 mixing

The Δm_s measurements are challenging due to high B_s oscillation frequency. It is about 40 times higher than $\Delta m_d = 0.508 \pm 0.004 \text{ ps}^{-1}$. The corresponding period of B_s oscillations ($\sim 100 \mu\text{m}$) requires to have enough events with the proper decay length resolution of the order of $20 - 25 \mu\text{m}$ to resolve these oscillations. Significance of the oscillation signal can be expressed using the following formula [10]:

$$\mathcal{S} \sim \sqrt{\frac{S\mathcal{E}\mathcal{D}^2}{2}} \cdot \exp\left(\frac{\Delta m_s^2}{2} \left(\frac{m_B}{\langle p \rangle} \sigma_L^2 + \left(t \frac{\sigma_p}{p}\right)^2\right)\right) \sqrt{\frac{S}{S+B}}, \quad (4)$$

where S (B) is the number of signal (background) candidates; \mathcal{E} is the tagging efficiency; \mathcal{D} is the tagging dilution; σ_L is the decay length resolution; σ_p/p is the relative momentum resolution. The tagging dilution is related to the mistag probability η : $\mathcal{D} = 1 - 2\eta$. Here, the tagging means determination of B_s flavor at the production time.

Both CDF and DØ used data samples corresponding to 1 fb^{-1} of integrated luminosity in the B_s oscillation analyses. The CDF strategy for collecting the B_s samples is based on the displaced track triggers and DØ exploited its muon system. The DØ experiment collected $26,710 \pm 556 B_s \rightarrow X\mu\nu D_s(\rightarrow \phi\pi)$ candidates shown in Fig. 1 (left). CDF reconstructed 3,600 hadronic $B_s^0 \rightarrow D_s^-(\pi^+\pi^-)\pi^+$ and 37,000 semileptonic $B_s^0 \rightarrow l^+ D_s^- X$ ($l = e, \mu$) decays. In both cases the modes $D_s^- \rightarrow \phi\pi^-$, $K^{*0}K^-$, $\pi^+\pi^-\pi^-$ were used. The hadronic $B_s^0 \rightarrow D_s^-\pi^+$ sample is shown in Fig. 1 (right). Semileptonic decays have much broader distribution on reconstructed B_s momentum resolution (3 – 20%) in comparison with fully reconstructed hadronic decays. Equation 4 shows that this resolution becomes important for large proper decay times. This decreases significantly power of the semileptonic B_s samples.

Calibration of the decay length resolution is essential for the B_s mixing analyses due to high Δm_s oscillation frequency. CDF utilized large sample of prompt D^+ mesons combined with one or three tracks from the primary vertex. This combination effectively simulates the $B_s^0 \rightarrow D_s^-(\pi^+\pi^-)\pi^+$ topology with known “ B_s^0 ” decay vertex allowing to

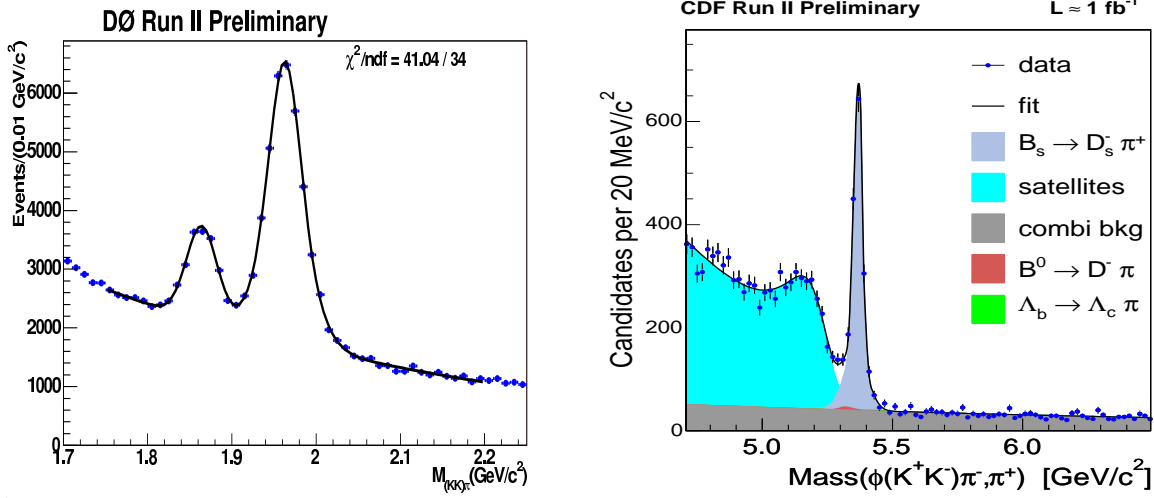


FIGURE 1. B_s^0 signal samples at DØ (left) and CDF (right).

calibrate the vertex resolution. DØ used $J/\psi \rightarrow \mu^+\mu^-$ sample where $\sim 70\%$ of J/ψ mesons are prompt. Overall decay length resolution scale factors have been determined using this sample: 1.0 for 72% of events and 1.8 for the rest. Simulated events were used to check a dependence of these scale factors from events topologies.

The tagging utilizes information from fragmentation track at the B_s reconstruction side (same-side tagging) or tries to determine the B flavor at the opposite side through partial reconstruction of its decay products (opposite-side tagging). The first technique is characterized by high efficiency ε and relatively low dilution \mathcal{D} . The opposite-side tagging has low efficiency but higher dilution. As can be seen from equation 4 the tagging power is determined by combination of these two parameters: $\varepsilon\mathcal{D}^2$. The opposite-side tagging was calibrated using B_d and B_u samples. The opposite-side tagging power was measured to be equal $\varepsilon\mathcal{D}^2 = 2.5 \pm 0.2\%$ at DØ and $\varepsilon\mathcal{D}^2 = 1.5 \pm 0.1\%$ at CDF. The same-side tagging was used at CDF with the power $\varepsilon\mathcal{D}^2 = 3.5\%$ (4.0%) for the hadronic (semileptonic) sample determined using the PYTHIA Monte Carlo simulated events. Particle identification used for selection of the fragmentation track significantly improved the same-side tagging power.

Probability for a B_s candidate to be reconstructed as oscillated (changed flavor with respect to the production time) or non-oscillated is following:

$$p_s^{\text{nos/osc}} = \frac{K}{2\tau_{B_s}} e^{-\frac{Kx}{c\tau_{B_s}}} (1 \pm \mathcal{D} \cos(\Delta m_s \cdot Kx/c)), \text{ where } K = \frac{p\mu D_s}{p_{B_s}}. \quad (5)$$

To detect a signal the amplitude scan method is used [11]. The probability is modified adding the parameter called amplitude \mathcal{A} to the cosine term: $\cos(\Delta m_s \cdot Kx/c) \cdot \mathcal{A}$. The amplitude \mathcal{A} is consistent with 1 for $\Delta m_s = \Delta m_s^{\text{true}}$ and otherwise consistent with 0. Fig. 2 shows the amplitude scans from DØ (left) and CDF (right). The DØ amplitude scan shows 2.5σ deviation from 0 at 19 ps^{-1} with the expected 95% CL limit 14.1 ps^{-1} . The CDF amplitude scan reveals the signal around 17 ps^{-1} with the expected 95% CL limit 25.3 ps^{-1} .

The log likelihood scans (Fig. 3) are in agreement with the amplitude scans. DØ sets the two-sided limit $17 < \Delta m_s < 21$ at 90% CL [12]. The probability of background fluctuation to give signal of the same significance is 5%. The corresponding CDF result is $17.01 < \Delta m_s < 17.84 \text{ ps}^{-1}$ at 90% CL with the probability of background fluctuation 0.2% [13]. The central value of B_s oscillation frequency from CDF is $\Delta m_s = 17.31^{+0.33}_{-0.18} (\text{stat.} \pm 0.07 (\text{syst.})) \text{ ps}^{-1}$ in good agreement with the theoretical SM predictions.

Lifetime difference in $B_s^0 - \bar{B}_s^0$ system

Measurements of the lifetime difference in $B_s^0 - \bar{B}_s^0$ system is possible through study of the B_s decays with common final states for B_s^0 and \bar{B}_s^0 . Examples of such final states are $J/\psi\phi$, $D_s^{(*)+}D_s^{(*)-}$ and K^+K^- (theoretical calculations are given in [28, 29, 30]). The Tevatron presented results on all these decays.

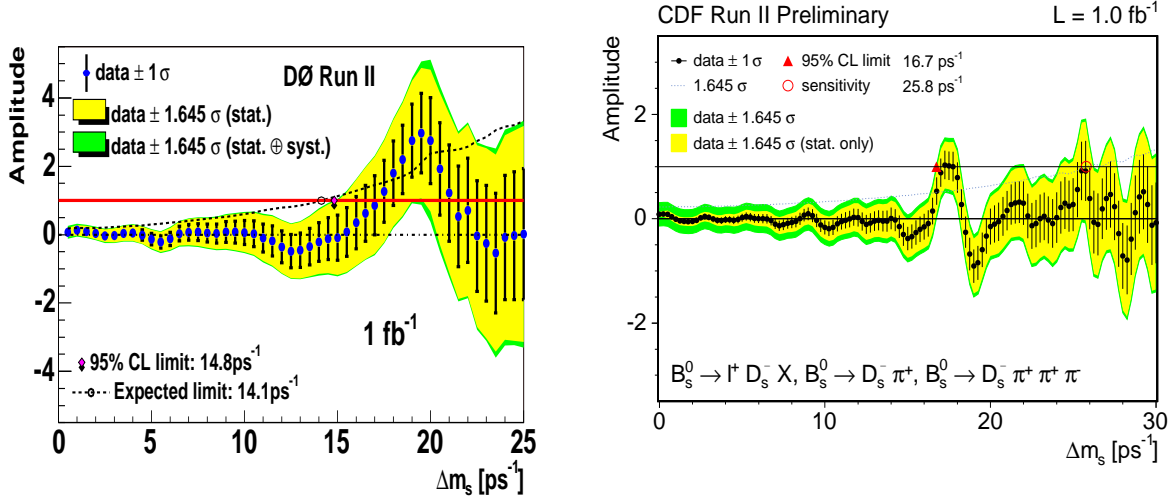


FIGURE 2. B_s^0 amplitude scan at DØ (left) and CDF (right).

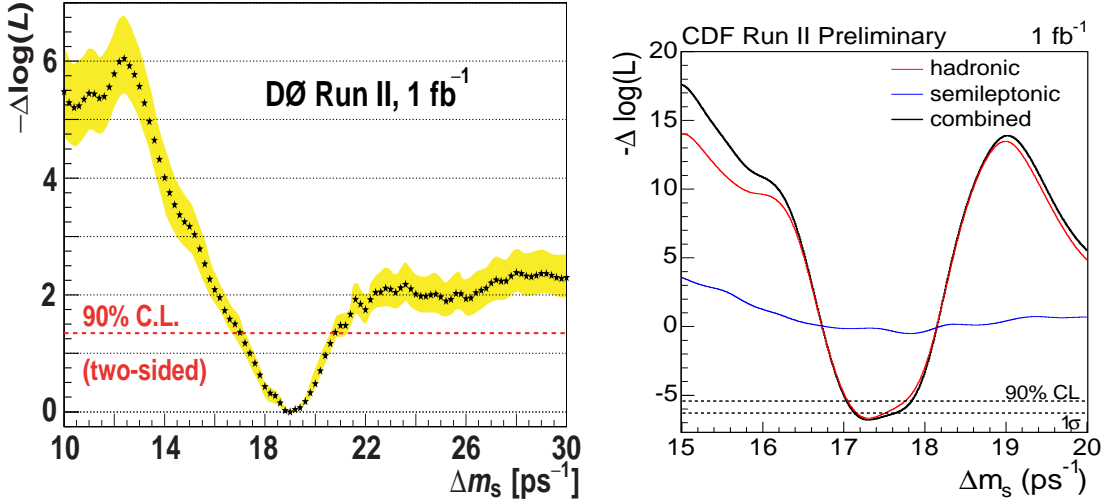


FIGURE 3. B_s^0 log likelihood scan at DØ (left) and CDF (right).

The decay $B_s \rightarrow D_s^+ D_s^-$ has pure CP-even final state. It is expected that the inclusive decays $B_s \rightarrow D_s^{(*)+} D_s^{(*)-}$ is also CP-even with 5% uncertainty. Then, a measurement of the branching ratio $Br(B_s \rightarrow D_s^{(*)+} D_s^{(*)-})$ leads to $\Delta\Gamma_{CP}$:

$$\frac{\Delta\Gamma_{CP}}{\Gamma} \sim \frac{2Br(B_s \rightarrow D_s^{(*)+} D_s^{(*)-})}{1 - Br(B_s \rightarrow D_s^{(*)+} D_s^{(*)-})/2}. \quad (6)$$

$\Delta\Gamma_{CP}$ is equal to $\Delta\Gamma_s$ assuming $\phi = 0$ (see Eq. 3).

CDF reconstructed 23.5 ± 5.5 candidates of the decay $B_s \rightarrow D_s^+ (\rightarrow \phi \pi^+) D_s^- (\rightarrow \phi \pi^-)$ (see Fig. 4 (left)). The branching ratio was measured relative to the decay $B_d \rightarrow D_s^+ D_s^-$: $Br(B_s \rightarrow D_s^+ D_s^-)/Br(B_d \rightarrow D_s^+ D_s^-) = 1.67 \pm 0.41 \pm 0.47$ [14]. Work on $\Delta\Gamma_{CP}$ measurement is in progress.

DØ used semileptonic D_s decays due to trigger requirements and reconstructed 19.3 ± 7.8 candidates of the decay $B_s \rightarrow D_s^{(*)+} (\rightarrow \phi \mu^+ \nu) D_s^{(*)-} (\rightarrow \phi \pi^-)$ (see Fig. 4 (right)). As a normalization process the decay $B_s \rightarrow D_s^{(*)+} (\rightarrow \phi \pi^+) \mu^+ \nu$ was chosen. The branching ratio $Br(B_s \rightarrow D_s^{(*)+} D_s^{(*)-}) = 0.071 \pm 0.032(\text{stat.})_{-0.025}^{+0.029}(\text{syst.})$ was measured. Using Eq. 6 the value $\Delta\Gamma_{CP}/\Gamma_s = 0.142 \pm 0.064(\text{stat.})_{-0.050}^{+0.058}(\text{syst.})$ was determined [15].

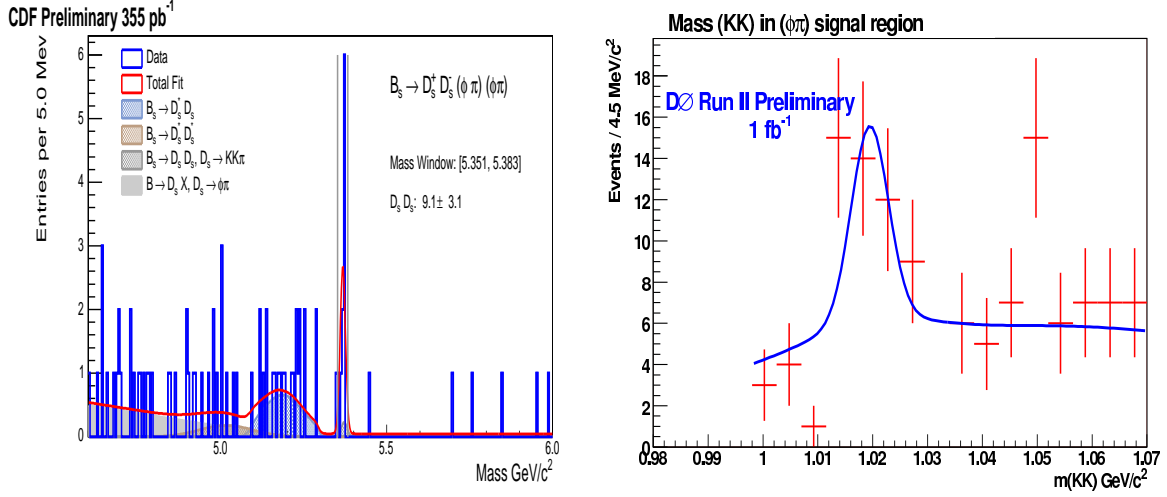


FIGURE 4. $B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ signal at CDF (left) and DØ (right).

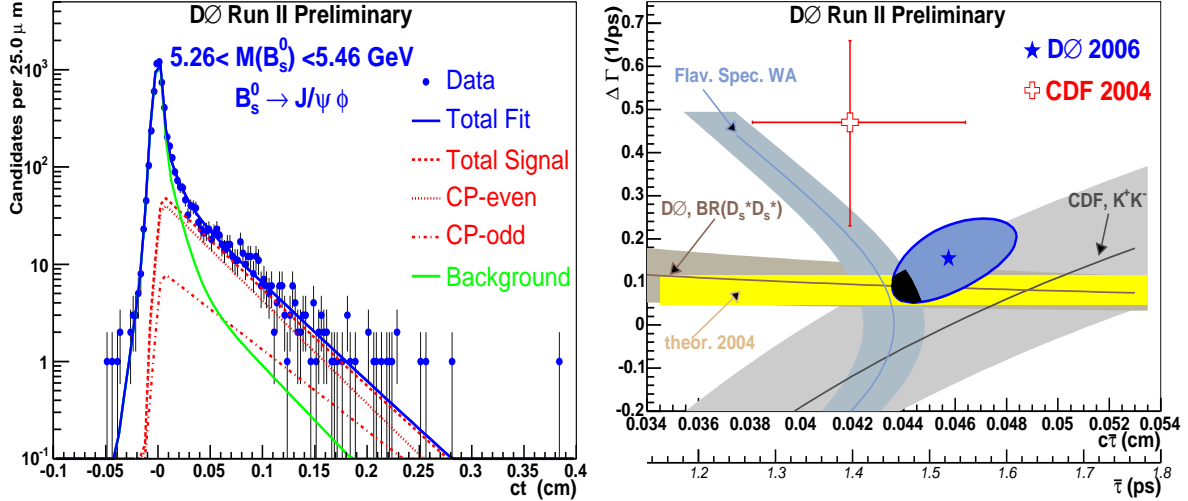


FIGURE 5. B_s CP-even and CP-odd lifetimes from DØ (left). Dependence of $\Delta\Gamma_s$ results from average B_s lifetime (right). “CDF 2004” and “DØ 2006” results refer to the $B_s \rightarrow J/\psi \phi$ analyses.

CDF determined the lifetime difference $\Delta\Gamma_{CP}(B_s \rightarrow K^+ K^-)/\Gamma_{CP}(B_s \rightarrow K^+ K^-) = -0.08 \pm 0.23 \pm 0.03$ [16] using the B_s lifetime measurement in the $K^+ K^-$ final state: $\tau(B_s \rightarrow K^+ K^-) = 1.53 \pm 0.18(stat.) \pm 0.02(syst.)$ ps [2].

The final state $J/\psi \phi$ is a mix of CP-even and CP-odd states which can be separated using angular distributions and the corresponding lifetimes can be measured (Fig. 5 (left)). The DØ result updated using 0.8 fb^{-1} is $\Delta\Gamma_s = 0.15 \pm 0.10(stat.)^{+0.03}_{-0.04}(syst.)$ [17].

Fig. 5 shows the $\Delta\Gamma_s$ results as functions of average B_s lifetime. The SM theoretical prediction [18] is shown as the horizontal band.

CP violation

The Tevatron experiments have possibilities to measure both direct CP violation and CP violation in mixing.

The direct CP violation can be measured using the decay $B_s^0 \rightarrow K^- \pi^+$ [30]. CDF collected a sample of hadronic two-body B decays which consists of $B_d^0 \rightarrow \pi^+ \pi^-$, $B_d^0 \rightarrow K^+ \pi^-$, $B_s^0 \rightarrow K^+ K^-$ and $B_s^0 \rightarrow K^- \pi^+$. The measurement

of CP violation using this sample has good accuracy and compatible with B-factories [19, 20]: $A_{CP}^{CDF}(B_d^0 \rightarrow K^+\pi^-) = -0.058 \pm 0.039(\text{stat.} \pm 0.007(\text{syst.}))$ [21]. The next step is an observation of $B_s^0 \rightarrow K^-\pi^+$ decay and determination of the direct CP violation in the B_s system which could be a model-independent probe for new phenomena [22, 30].

DØ obtained the world most precise result on the CP violation in mixing in B_d system: $\Re(\epsilon_B)/(1+|\epsilon_B|^2) = a_{fs}^d/4 = -(1.1 \pm 1.0 \pm 0.7) \times 10^{-3}$ [23]. Changes in the magnet polarities during different periods of data taking help to reduce systematic uncertainties in the CP violation measurements. This work was an important step toward the CP violation in mixing measurement in B_s system [24].

CONCLUSION

Complex studies of the B_s properties are being conducted using the CDF and DØ detectors at the Tevatron Collider. The results on B_s mixing, lifetime difference and first steps toward the CP violation measurements in B_s system were discussed in details.

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